EXTRATERRESTRIAL RADIO NOISE AND ITS EFFECT ON RADAR PERFORMANCE

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SUMMARY

In this paper, the flux densities of radio frequency radiation from the quiet sun and other cosmic noise sources are presented as a function of frequency. The conversion of flux density to apparent antenna temperature is discussed An evaluation is made of UHF radar system degradation, i.e., the reduction of radar-range capability, due to the presence of the sun, discrete radio stars and distributed noise sources in the Galaxy.

1. INTRODUCTION

The sun, the galactic center and discrete radio stars are astronomical sources which emit electromagnetic waves in the radio frequency spectrum. When cosmic radiation is intercepted by an antenna and enters into a receiver, it affects the system sensitivity in the same manner as thermal receiver noise. The effective receiver noise temperature is a function of the actual receiver temperature, the background noise intercepted by the antenna and the lossiness of the networks connecting the receiver to the antenna. Since extraterrestrial radio noise contributes to this temperature and hence may tend to reduce system sensitivity, it must be taken into account in the analysis of radar systems.

The other sources of external radio frequency noise are atmospheric and man made. Atmospheric noise is pre dominant at frequencies less than approximately 20 MHz. Above this frequency, cosmic noise prevails. Man-made noise, on the other hand, can be important for HF radio frequency systems located near urban-industrial areas.

The existence of celestrial radio radiation was first noted by Jansky (1932) who found that antenna noise, at a frequency of approximately 20 MHz, exhibited a diurnal variation both in magnitude and direction. Further investigation revealed that the Milky Way was the source of the radiation (Jansky, 1933).

Experimental investigations of galactic and solar radio noise gained momemtum following the termination of World War II. The first maps of the background radiation from the sky were made at 160 MHz by Reber (1944). Detailed surveys of the sky background radiation made during the early days of radio astronomical studies were at a frequency of 64 MHz (Hey et al., 1948), 81 MHz (Baldwin, 1955), 100 MHz (Bolton and Westfold, 1950), 250 MHz (Ko and Kraus, 1955), 480 MHz (Reber, 1948), 600 MHz (Piddington and Trent, 1956) and 910 MHz (Denisse et al., 1955).

In this paper, radiation from cosmic noise sources, expressed in terms of flux density, is converted into apparent antenna temperature. The degradation in radar performance resulting from the increase in the apparent temperature, i.e. in the system noise level, is evaluated.

2. DISCRETE NOISE SOURCES

2.1 APPARENT ANTENNA TEMPERATURE

The distribution of energy for frequencies in the radio spectrum of a black-body radiator, according to the Rayleigh-Jeans radiation law, is

$$b = \frac{2\,K\,T_b}{\lambda^2} \tag{1}$$

where b is the energy emitted per steradian per second by a unit area of surface, expressed in $W/m^2/Hz$/steradian, k is Boltzmann's constant (1.38×10^{-23} W-sec/°K), T_b is the absolute temperature of the black body, and λ is the radiated wavelength.

The flux density, S, which is a measure of the radiation from a discrete source whose angular dimension is small with respect to the antenna beamwidth, is given by

$$S = b\,\Omega \tag{2}$$

where Ω is the solid angle, in steradians, subtended by the source at the point of observation and S is in $W/m^2/Hz$.

The power available at a receiving system is therefore

$$P = (1/2)\,S\,A_e B \tag{3}$$

where A_e is the effective area of the receiving antenna and B is the receiver bandwidth. The factor of one-half enters into this relationship simply because an antenna is generally capable of accepting only one of two orthogonal polarizations.

According to Nyquist's formulation of the thermal noise concept, the thermal noise intercepted by an antenna is

$$P = K\,T_a\,B \tag{4}$$

where T_a is the apparent antenna temperature.

From Equations (3) and (4) it follows that the apparent antenna temperature can be expressed in terms of the flux density by the function

$$T_a = \frac{S A_e}{2k} \tag{5}$$

Substituting Equations (1) and (2) in this relationship, it is seen that the apparent antenna temperature can also be defined in terms of the black-body temperature of a distance source by

$$T_a = \frac{T_b \; \Omega A_e}{\lambda^2} \tag{6}$$

The apparent temperature of an antenna is usually composed of contributions from many external noise sources such as the sky background radiation, the radiation from a warm earth scattered by particles into the mainlobe of an antenna, the leakage from a warm earth into the minor lobe pattern of an antenna, and the reradiation from an absorbing medium. Mathematically, the apparent temperature is given by

$$T_a = T_{a1} + T_{a2} + T_{a3} + \ldots T_{an} \tag{7}$$

where T_{ai} is the apparent noise temperature resulting from one of the above sources.

If the celestial noise radiator has an angular area larger than the angular dimensions of the antenna beamwidth, then neglecting other sources, the temperature of this source determines the antenna temperature. If the angular size of the source is small compared to the antenna angular beam size, then, to a first approximation, the apparent antenna temperature due to this source is given by

$$T_a = \frac{A_b}{A_a} \; T_b \tag{8}$$

where A_a and A_b are the angular areas of the antenna beam and celestial body, respectively.

With reference to Equation (6), a more accurate determination of the apparent antenna temperature would be obtained by integrating over solid angle such that

$$T_a = \frac{1}{4\pi} \int G T_b \; d\Omega \tag{9}$$

where G is the antenna gain defined by

$$G = \frac{4\pi A_e}{\lambda^2} \tag{10}$$

2.2 THE SUN

The sun radiates high-intensity electromagnetic wave noise greatly in excess of the black-body intensity of 6000° K deduced from optical and thermal data. If the radio noise from the sun is observed continuously, it is found that, during sunspot activity, irregular increases of radio noise can occur lasting for periods of several days at a time. The radio noise is enhanced on the order of 10-20 dB greater than the base level of the quiet sun.

In addition to the increase in the general level of radio noise, when sunspots are visible and active, sudden bursts of a few seconds duration and rapid fluctuations of the flux density are a commom characteristic of a solar disturbance. When solar noise is examined on several frequencies, in the majority of cases, a noise burst appears on one frequency but not on the others. When the noise burst does appear on several frequencies, most often it first shows up on the highest frequency and then, after a few seconds interval, on the lower frequencies.

The theoretical total flux density in the radio frequency spectrum of solar energy received at the earth's surface in terms of apparent black-body temperature is, according to Equations (1) and (2),

$$S = \frac{2 k T_b \pi}{\lambda^2} \left(\frac{r}{R}\right)^2 \tag{11}$$

where

$$\Omega = \pi \left(\frac{r}{R}\right)^2 = 6.79 \times 10^{-5} \text{ steradian} \tag{12}$$

and where r is the radius of the photosphere (6.96×10^5 km) and R is the mean earth-sun distance (1.497×10^8 km). The numerical evaluation of Equation (11) is

$$S = 1.88 \times 10^{-27} \frac{T_b}{\lambda^2} \; W/m^2/Hz \tag{13}$$

Figure 1 is a simplified chart which converts the total solar flux density into apparent black-body temperature. As an example, at a frequency of 1000 MHz, a flux density of 2.1 x 10^{-20} W/m^2/Hz, is equivalent to a black-body temperature of approximately 10^6 °K for a disk subtending the same diameter as the sun.

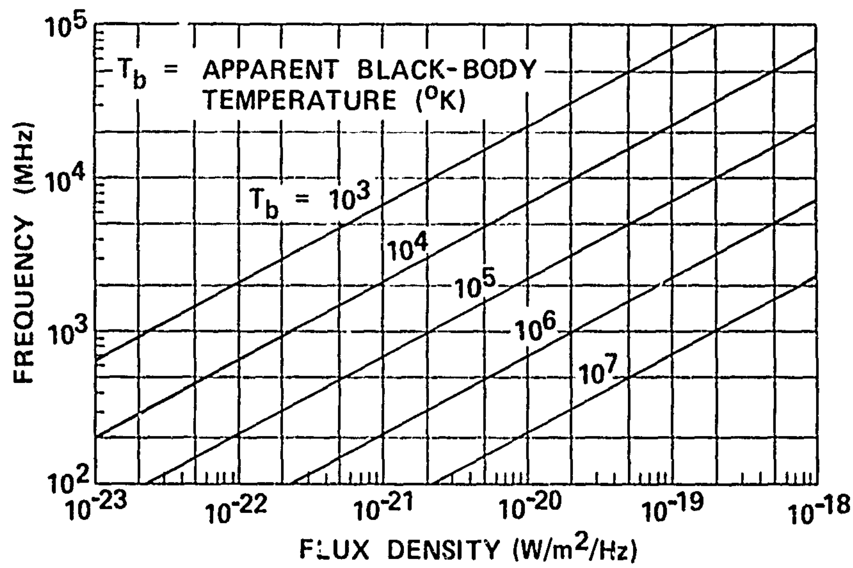

Figure 1. Conversion of Total Solar Flux Density into Apparent Black-Body Temperature

Experimental measured values of the apparent temperature of the quiet sun over a wide range of frequencies are shown in Figure 2 (Pawsey and Smerd, 1953; Maxwell et al., 1959). The solid line through the observational data, which is the assumed average linear function between apparent temperature and wavelength, can be expressed by

$$\text{Log } T_b = \text{Log } b_1 + b_2 \text{ Log } \lambda \tag{14}$$

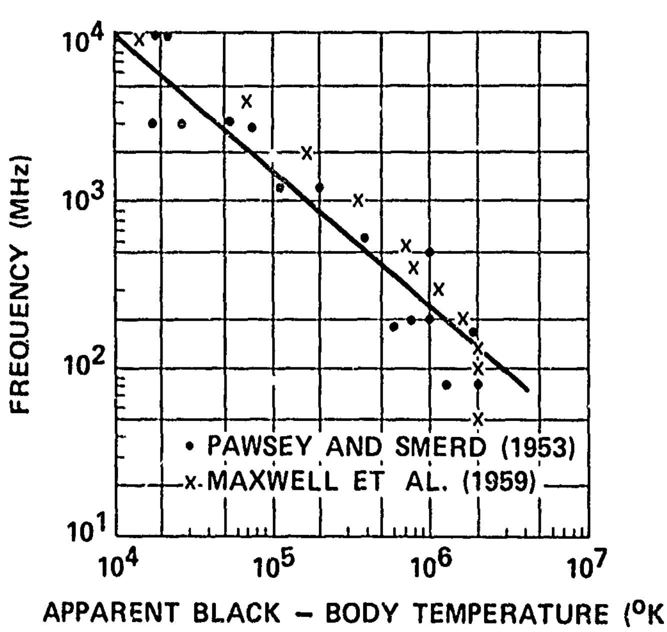

Figure 2. Experimental Values of the Apparent Black-Body Temperature of the Quiet Sun

It is noted that this expression is the general form of the equation of a line where b_2 is its slope and b_1 is the log T_b axis intercept. The numerical value of the slope, $b_2 = 1.245$, is obtained by direct measurement with an arbitrary scale in which the logarithmic coordinate axes are disregarded.

From Figure 2, it is seen that, at $\lambda = 0.2$ m, $T_b = 10^5$ °K and hence $b_1 = 7.417 \times 10^5$. It should be noted that when the wavelength is expressed in centimeters, $b_1 = 2.4 \times 10^3$.

The relationship between the apparent disk temperature and wavelength is therefore

$$T_b = 7.417 \times 10^5 \, \lambda^{1.245} \quad (15)$$

where λ is in meters and T_b is in °K.

Combining Equations (13) and (15), it is seen that the flux density is directly proportional to frequency and is given by

$$S = \frac{1.394 \times 10^{-21}}{\lambda^{0.755}} \; \mathrm{W/m^2/Hz} \quad (16)$$

Figure 3 is a plot of this relationship. At a frequency of 200 MHz, the flux density of the quiet sun is approximately 1.03×10^{-21} W/m^2/Hz. This value compares favorably with experimental measurements of 8×10^{-22} W/m^2/Hz (Dodson et al., 1953). As shown in Figure 3, at 400 MHz the flux density increases to 1.7×10^{-21} W/m^2/Hz.

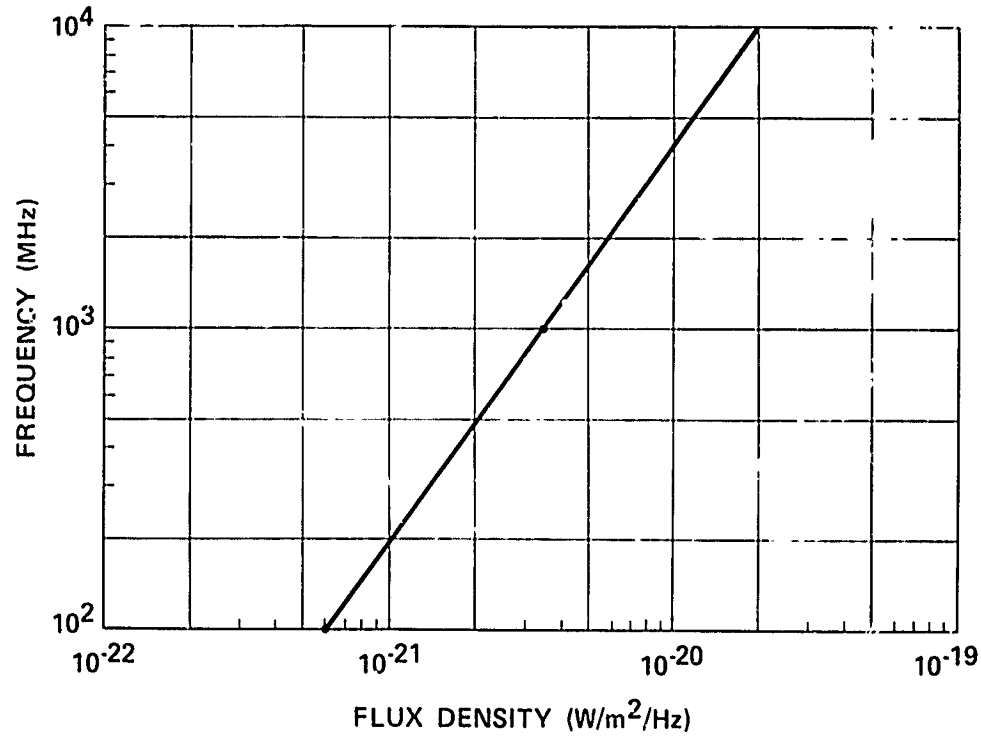

Figure 3. The Flux Density of the Quiet Sun as a Function of Frequency

2.3 NONSOLAR SOURCES

The observations of the fluctuations in 64 MHz radiation emanating from a region in the constellation of Cygnus, by Hey et al. (1946), announced the possible existence of discrete noise sources of extraterrestrial origin. The amplitude and the fading rate of the fluctuations were similar in appearance to the radiation from the sun during sunspot activity. Ryle and Smith (1946) found that a source in Cassiopeia was more intense than Cygnus A and were able to show that the radiation from the two sources were randomly polarized.

A rather complete catalogue of positions and intensities of discrete ratio stars has been compiled by Pawsey (1955). The major sources which can be detected from locations in both the northern and southern hemisphere are listed in Table 1.

Figure 4 is a plot of the flux density of the discrete ratio stars. It should be mentioned that the flux densities are twice that observed in one plane of polarization. At 200 MHz, the total radiation from Cassiopeia and Cygnus A, which are the more intense sources, is approximately 1.05×10^{-22} W/m^2/Hz and 6.6×10^{-23} W/m^2/Hz, respectively. It can be shown that the slope of the frequency flux curve through Cassiopeia and Cygnus-A can be expressed approximately by the function, $S \propto f^{-0.81}$.

TABLE 1

EQUATORIAL COORDINATES OF MAJOR DISCRETE RADIO STARS

Constellation	Declination	Right Ascension
Andromeda	40° 50' ± 20'	$00^h\,40^m15^s \pm 30^s$
Cassiopeia	58° 32.1' ± 0.7'	$23^h\,21^m12^s \pm 1^s$
Centaurus	-42° 46' ± 2'	$13^h\,22^m30^s \pm 4^s$
Cygnus	40° 35' ± 1'	$19^h\,57^m45.3^s \pm 1^s$
Perseus	41° 22' ± 30'	$03^h\,15^m15^s \pm 1.5^m$
Taurus	22° 00' ± 3'	$05^h\,31^m29^s \pm 2.5^s$
Virgo	12° 44' ± 6'	$12^h\,28^m15.5^s \pm 2.5^s$

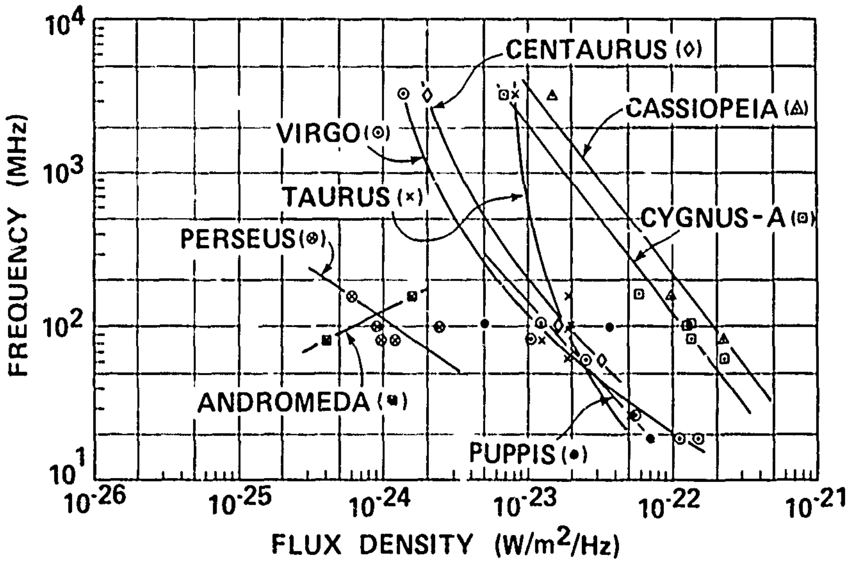

Figure 4. Flux Density of Discrete Radio Sources as a Function of Frequency

3. DISTRIBUTED NOISE SOURCES

3.1 APPARENT ANTENNA TEMPERATURE

When the source of radiation consists of many individual radiators spatially distributed, the flux density is now defined by the integral

$$S = \iint b(\theta,\phi)\,d\Omega \qquad (17)$$

where the integration is taken over the whole solid angle occupied by the sources.

Since the effective antenna area is a function of aspect angles (θ,ϕ), the received power becomes, according to Equation (3).

$$P = 1/2\, B \iint A_e(\theta,\phi)\; b(\theta,\phi)\; d\Omega \tag{18}$$

The equivalent antenna temperature is, therefore, given by

$$T_a = \frac{1}{\lambda^2} \iint T_b(\theta,\phi) \quad A_e(\theta,\phi)\; d\Omega \tag{19}$$

3.2 GALACTIC SOURCES

The results of observations of the intensity and distribution of radio-frequency radiation from the galaxy at frequencies from 19.5 to over 1000 MHz, collected by Piddington (1951), are presented in Figure 5. The slope of the spectrum curve is expressed by $T_b \propto f^{-\gamma}$ where γ is the constant for the portion of the curve in question. The constant γ, has a value of 2.73 for the central portion of curve B and 2.51 for the central portion of curve A.

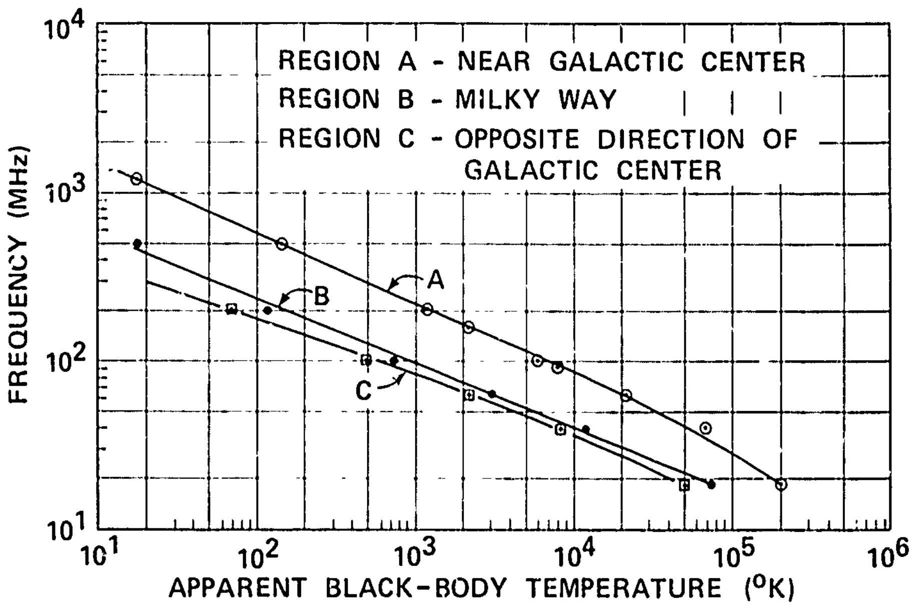

Figure 5. Apparent Black-Body Temperature of Galactic Radiation (After Piddington, 1951)

The coordinates of the different regions are given in Table 2. Since the positions of the noise sources were given in galactic coordinates, the conversion to equatorial coordinates was performed from the chart furnished by Pawsey and Bracewell (1955). Region A is near the center of the galaxy, while region B is in the Milky Way. Region C is in the oopesite direction of the galactic center.

TABLE 2

DISTRIBUTED NOISE SOURCES

Region	Galactic Coordinates	Equatorial Coordinates
A	Latitude = -2°	Declination = -26°
	Longitude = 330°	Right Ascension = 17^h35^m
B	Latitude = 0°	Declination = 0°
	Longitude = 180°	Right Ascension = 6^h40^m
C	Latitude = -30°	Declination = -29°
	Longitude = 200°	Right Ascension = 5^h30^m

From the galactic radiation measurements at frequencies of 40, 90 and 200 MHz, Moxon (1946) found that, when the antenna was directed towards the maximum noise radiation at the galactic equator, the relationship between the apparent black-body temperature and frequency was $T_b \propto f^{-2.7}$. When the antenna was aimed away from the galactic equator, the temperature-frequency proportionate relationship was $T_b \propto f^{-2.1}$. It was also noticed that the frequency exponent was practically insensitive to galactic longitude variations.

Since the flux density is directly proportional to the square of frequency and to the apparent black-body temperature [see Equations (1) and (2)], it is evident that, for galactic noise, the flux density is inversely proportional to frequency. In other words, the flux density decreases with increasing frequency which is contrary to solar noise frequency dependency.

4. SYSTEM DEGRADATION BY COSMIC RADIATION

An increase in system noise temperature, in essence, alters the maximum range capability of a radar system. According to the radar equation, the maximum range is defined by

$$R_{max} \propto \left(\frac{P_t}{S_{min}}\right)^{1/4} \propto \left(\frac{1}{T_s}\right)^{1/4} \qquad (20)$$

where P_t is the transmitted peak power, S_{min} is the minimum detectable signal and T_s is the effective systen. noise temperature.

The effective system noise temperature can be calculated from the expression

$$T_s = \frac{T_a}{L_r} + \left(1 - \frac{1}{L_r}\right) T_L + \left(F_o - 1\right) T_o \qquad (21)$$

where L_r is the line loss factor from antenna to receiver (can be assumed to be approximately 2 dB), T_L is the temperature of the receive transmission line components (usually 290°K), T_o is the reference noise temperature (290°K), and F_o is the noise figure of the receiver referred to T_o. The apparent noise temerature of the antenna, T_a, is assumed to consist of contributions solely from extraterrestrial noise sources. The other contributions, described in Equation (7), have been neglected.

Table 3 shows the apparent antenna temperatures at 100 and 1000 MHz and the reduction in range for a two-way path caused by the quiet sun, the major radio stars, and distributed galactic noise regions. The calculations are based on an effective antenna aperture of 309 m^2 (25.6-m or 84-ft-diameter parabolic antenna with an antenna efficiency factor of 0.6) and a receiver noise figure of 1.5 dB.

TABLE 3

REDUCTION IN RANGE FOR A TWO-WAY PATH DUE TO THE PRESENCE OF COSMIC NOISE SOURCES

Radio Source	Apparent Antenna Temperature (°K)		Reduction in Range (%)	
	100 MHz	1000 MHz	100 MHz	1000 MHz
Sun (Quiet)	6710	39,200	52.5	69.1
Cassiopeia	2070	319	38.0	14.7
Cygnus-A	1340	201	32.2	10.6
Taurus	201	103	10.5	6.2
Centaurus	196	38	10.3	2.5
Virgo	134	24	7.6	1.6
Center of Galaxy	6600	25	52.4	1.7
Milky Way	1050	< 10	28.9	0.7

It is obvious that, for this example, the sun is the major source of interference at the higher frequency, while Cassiopeia, Cygnus-A, and Taurus are somewhat less significant. The appearance of the other radio stars, the galactic center, and the Milky Way in the antenna beam does not introduce any appreciable system deterioration except at 100 MHz. The interference from all cosmic radio noise sources, except the sun, is reduced as the transmission frequency is increased.

5. CONCLUSIONS

The extraterrestrial radio noise sources, such as the sun, radio stars, galactic center, and the Milky Way, can degrade the sensitivity of radar systems by raising the background noise level. Except for the sun, the interference of the cosmic noise sources is reduced for frequencies above 1000 MHz.

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